SAND2016-0722PE

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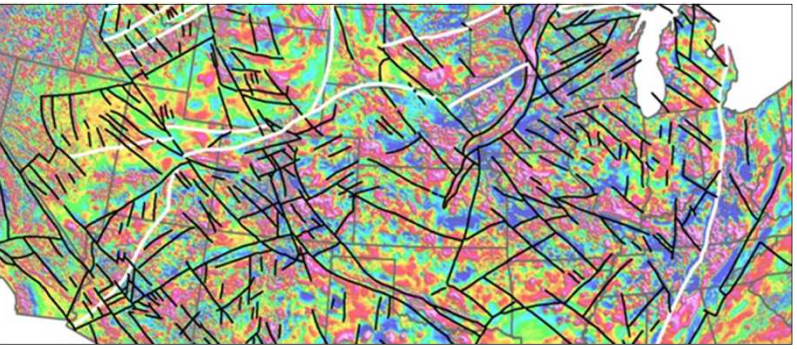

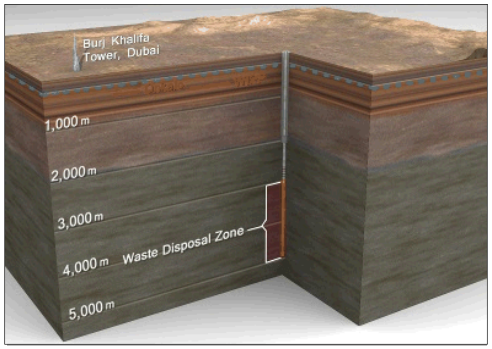

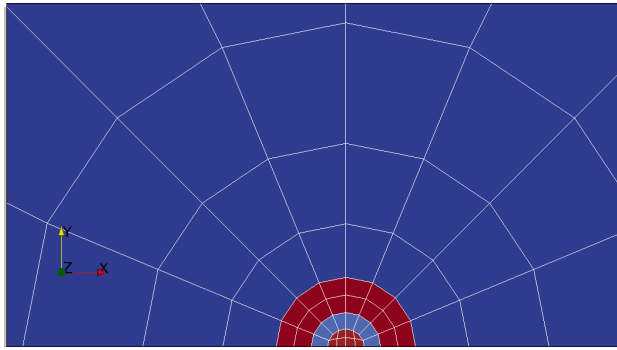

DBFT Site Characterization Overview

Williston Basin and Superior Craton

Kris Kuhlman, Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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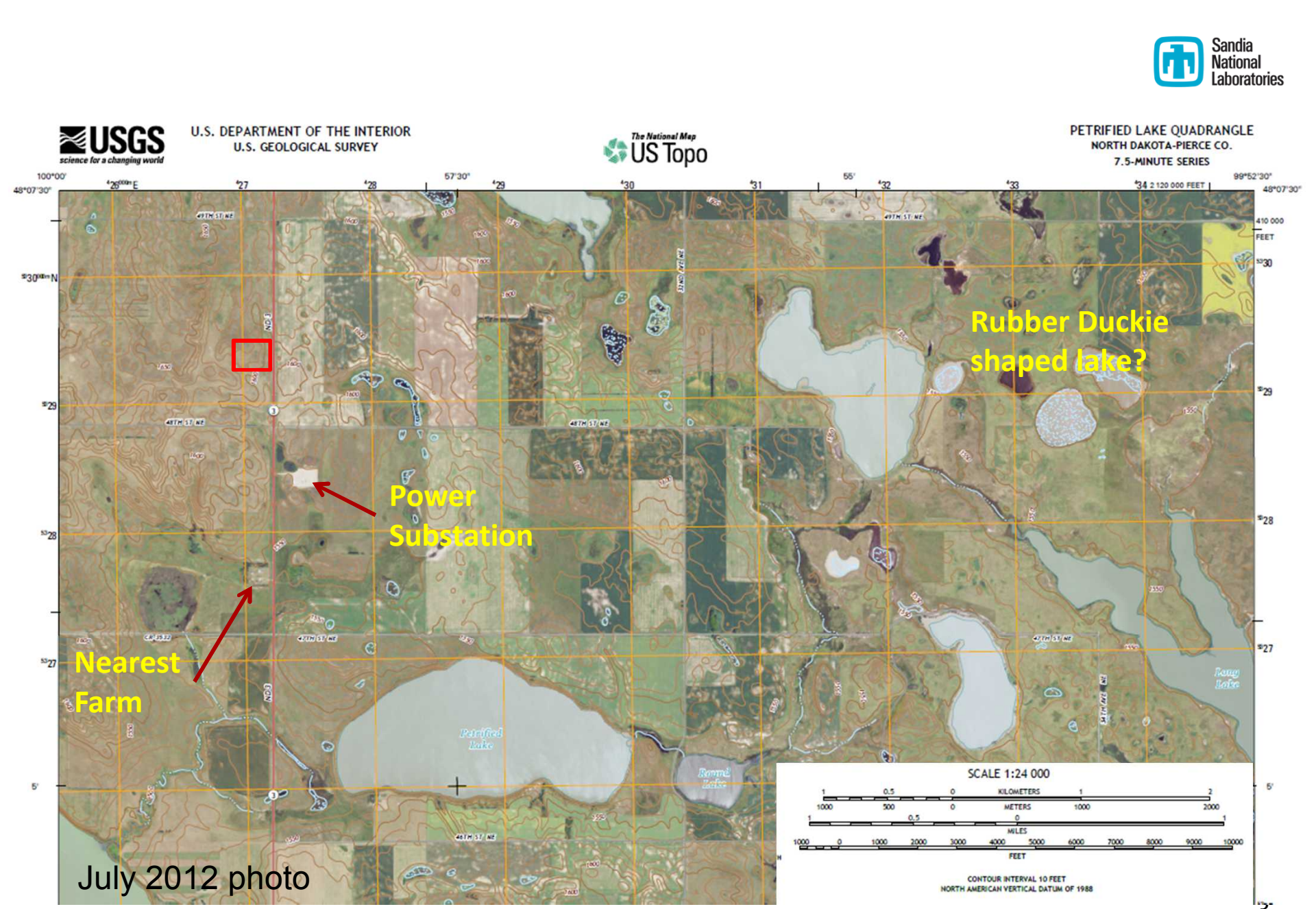
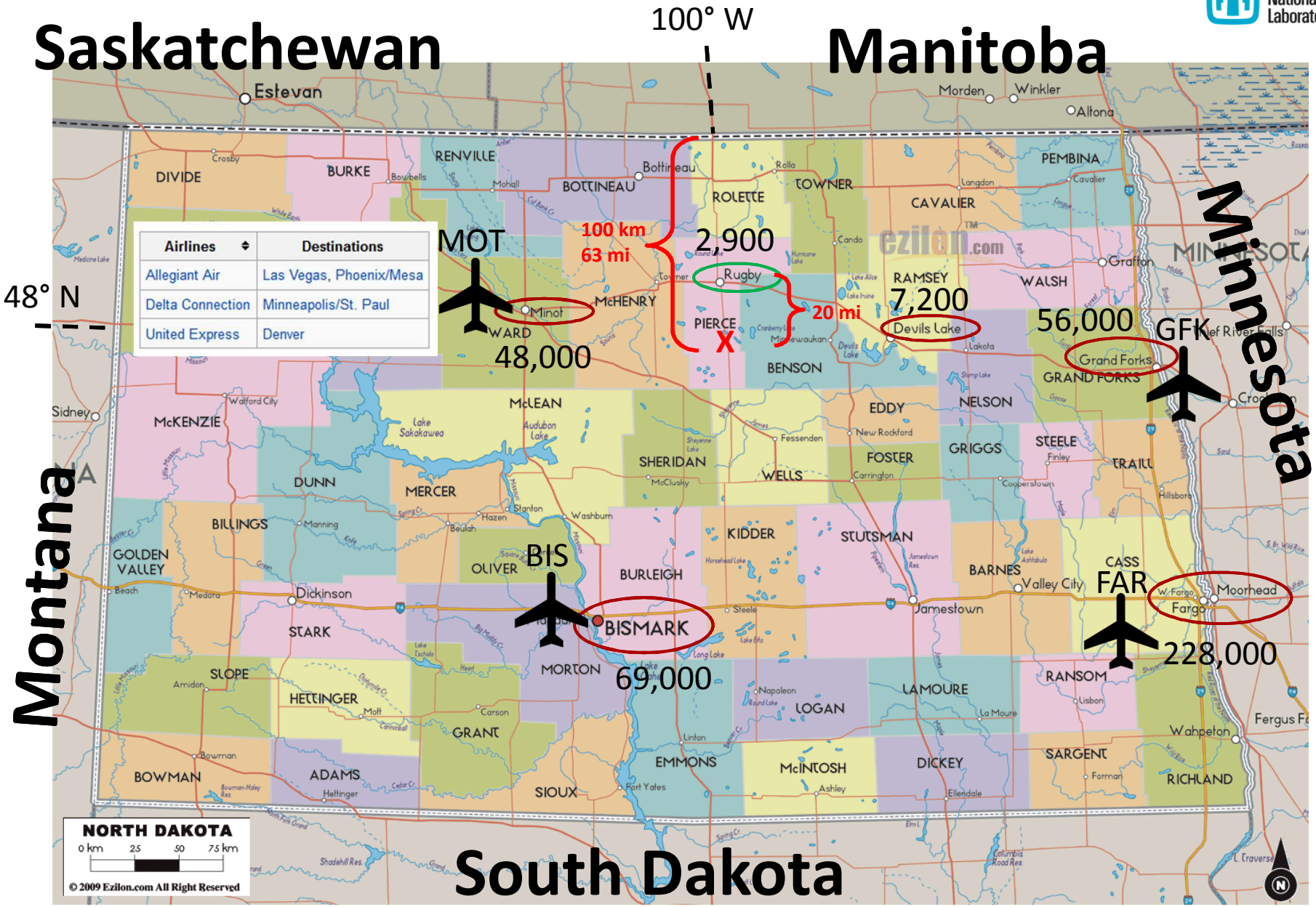
ND-3
Google street view Oct 2012


U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY
USGS
science for a changing world
The National Map
US Topo
PETRIFIED LAKE QUADRANGLE
NORTH DAKOTA-PIERCE CO.
7.5-MINUTE SERIES
Rubber Duckie shaped lake?
Power Substation
Nearest Farm
July 2012 photo
SCALE 1:24 000
KILOMETERS
METERS
MILES
FEET
CONTOUR INTERVAL 10 FEET
NORTH AMERICAN VERTICAL DATUM OF 1988


Saskatchewan
100° W
Manitoba
Minnesota
Montana
South Dakota
48° N
Airlines
Destinations
Allegiant Air
Las Vegas, Phoenix/Mesa
Delta Connection
Minneapolis/St. Paul
United Express
Denver
MOT
Minot
48,000
100 km
63 mi
2,900
Rugby
20 mi
7,200
Devils Lake
56,000
GFK
Grand Forks
BIS
BISMARK
69,000
FAR
Fargo
Moorhead
228,000
X
Estevan
Morden
Winkler
Altona
DIVIDE
BURKE
RENVILLE
BOTTINEAU
ROLETTE
TOWNER
PEMBINA
CAVALIER
RAMSEY
WALSH
Grafton
MINNESOTA
MCHENRY
PIERCE
BENSON
EDDY
NELSON
GRAND FORKS
WARD
McLEAN
SHERIDAN
WELLS
FOSTER
GRIGGS
STEELE
TRAILL
Sidney
McKENZIE
DUNN
MERCER
KIDDER
STUTSMAN
BARNES
CASS
BILLINGS
GOLDEN VALLEY
OLIVER
BURLEIGH
Dickinson
Valley City
Jamestown
STARK
SLOPE
HETTINGER
MORTON
LAMOURE
RANSOM
LOGAN
GRANT
Wahpeton
BOWMAN
ADAMS
EMMONS
McINTOSH
DICKEY
SARGENT
RICHLAND
SIOUX
NORTH DAKOTA
0 km 25 50 75 km
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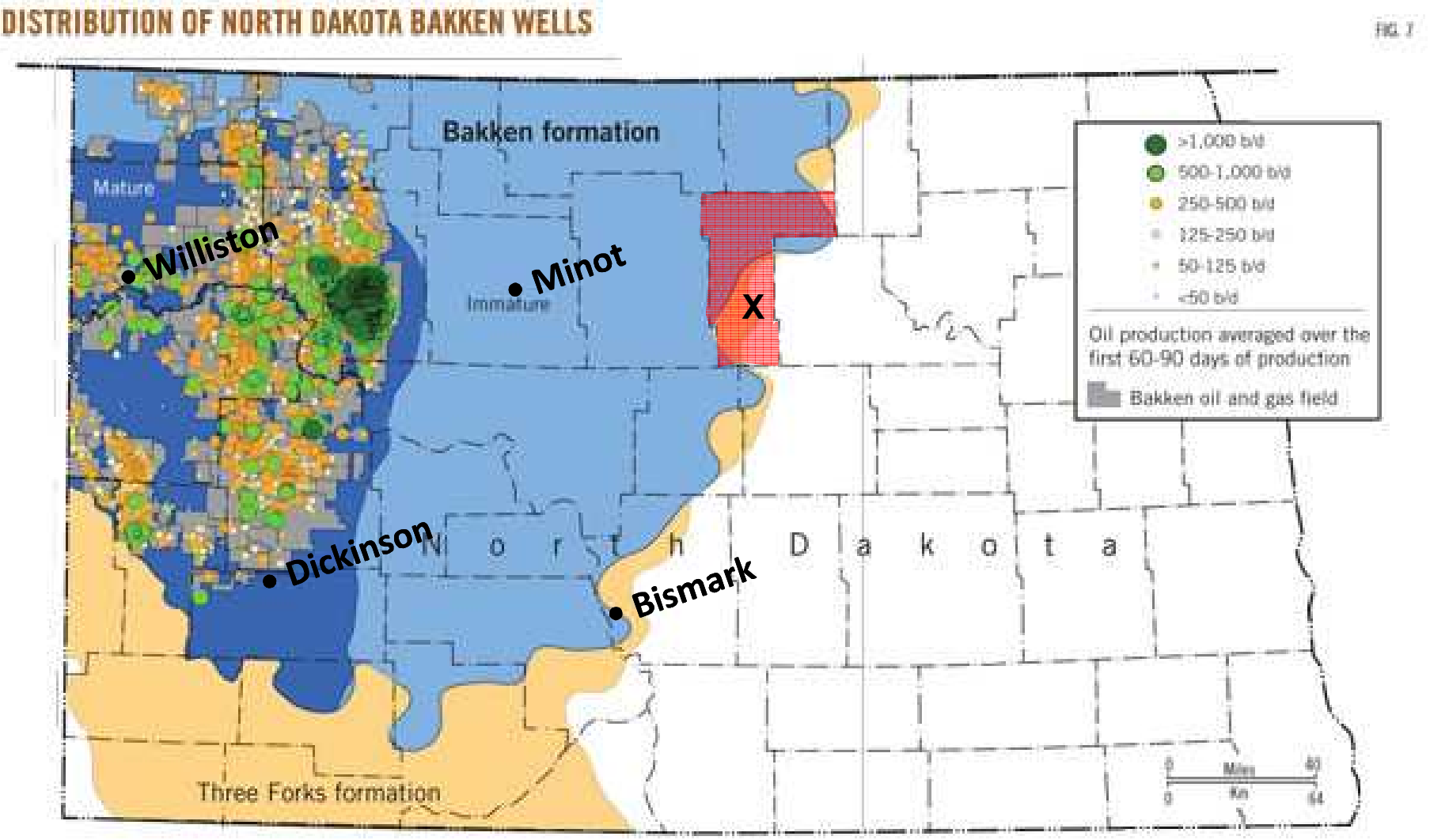
Bakken Oilfield is ≥100 Miles West



Source: Reference E

Laurentian Surface Water Divide

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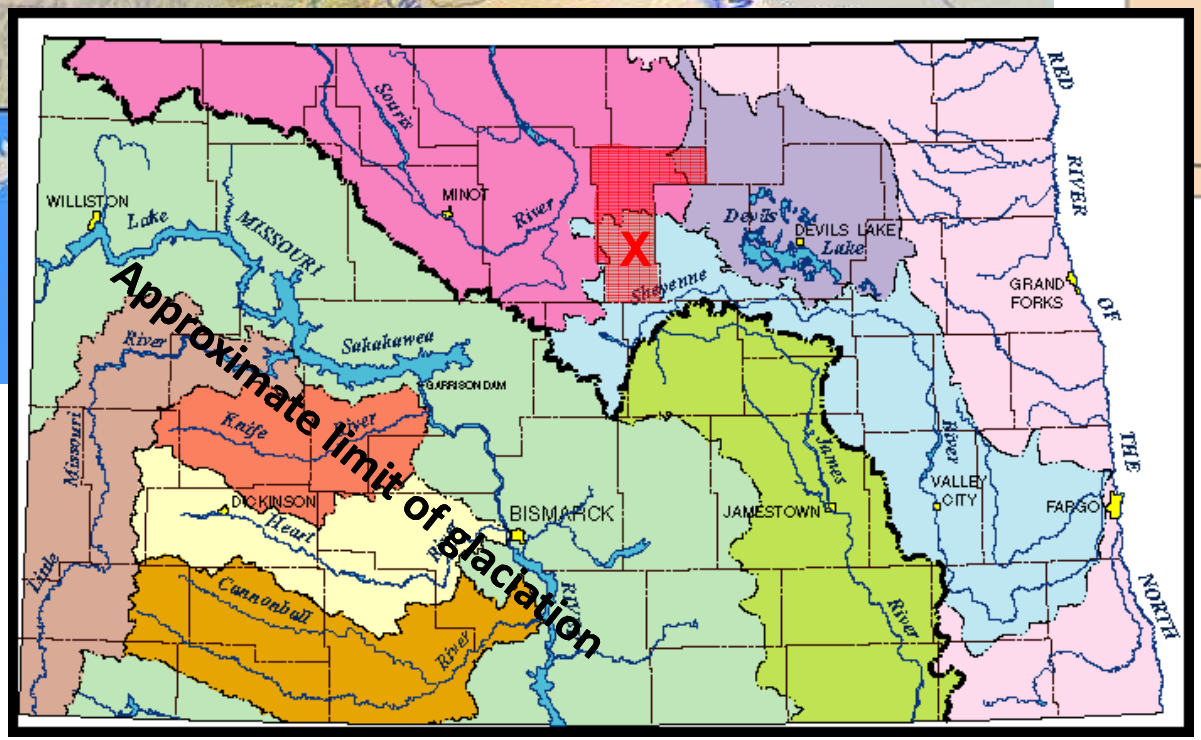

Sheyenne River Watershed
(drains to Hudson Bay)

Site elevation (AMSL)
1,600 ft / 490 m

Assembly of North American Craton

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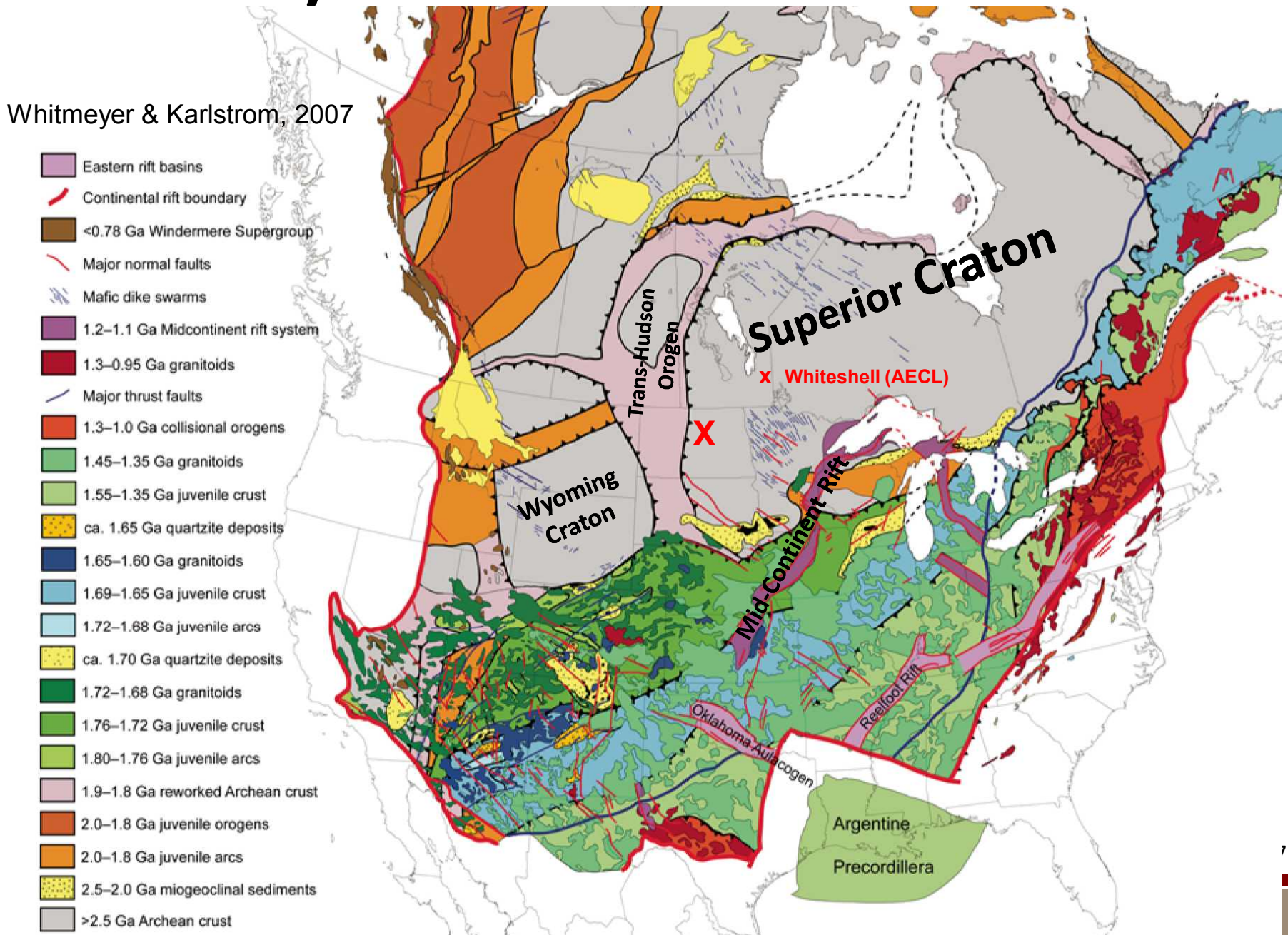
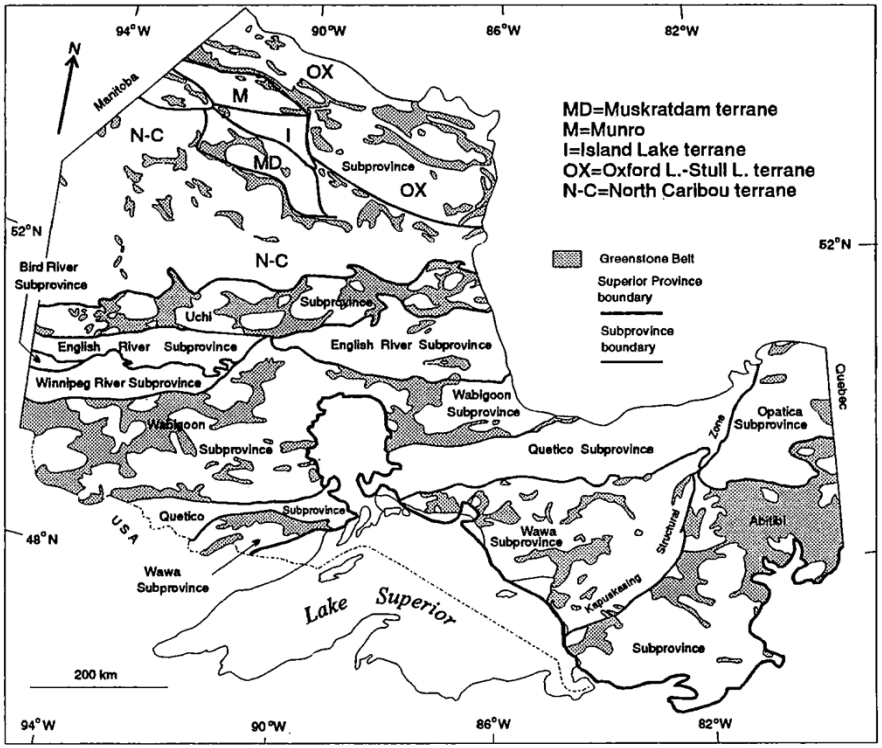
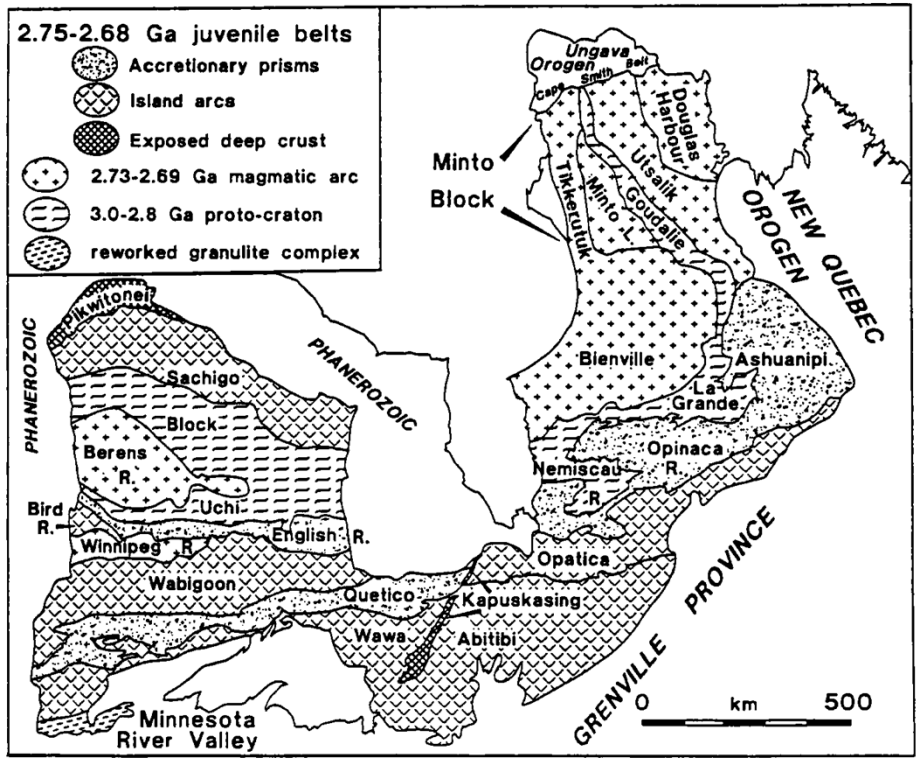


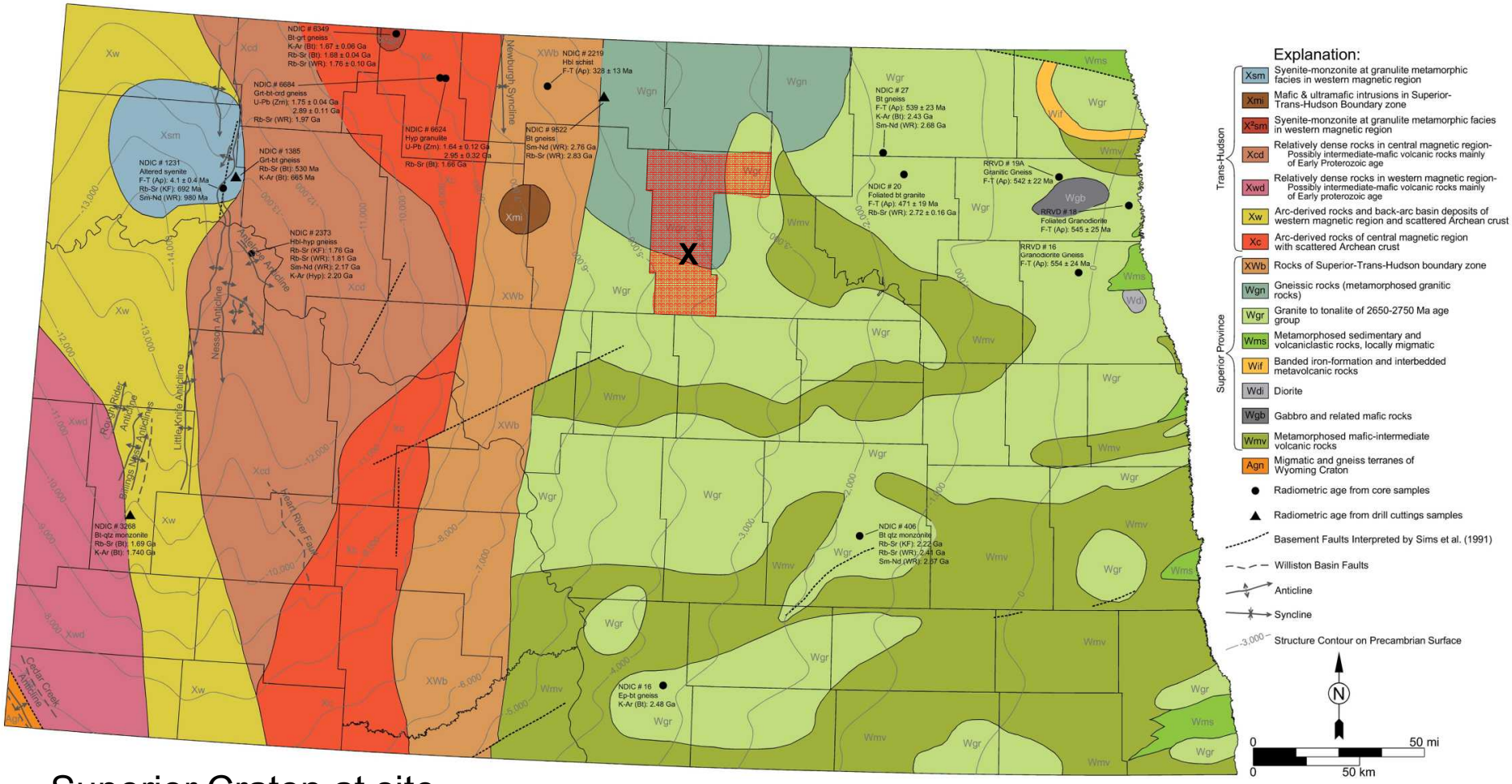
Superior Craton Geology is Also Complex





"Archean Crustal Evolution" Condie [Ed], Elsevier, 1994.

Pre-Cambrian ND geology



Superior Craton at site

- ≈2.7 billion years old
- Gneissic rocks (metamorphosed granitic rocks)
- Analogous to exposed shield in MN & Manitoba/Ontario

NDGS GI-160 (2012)

ND Depth to Basement (2009)

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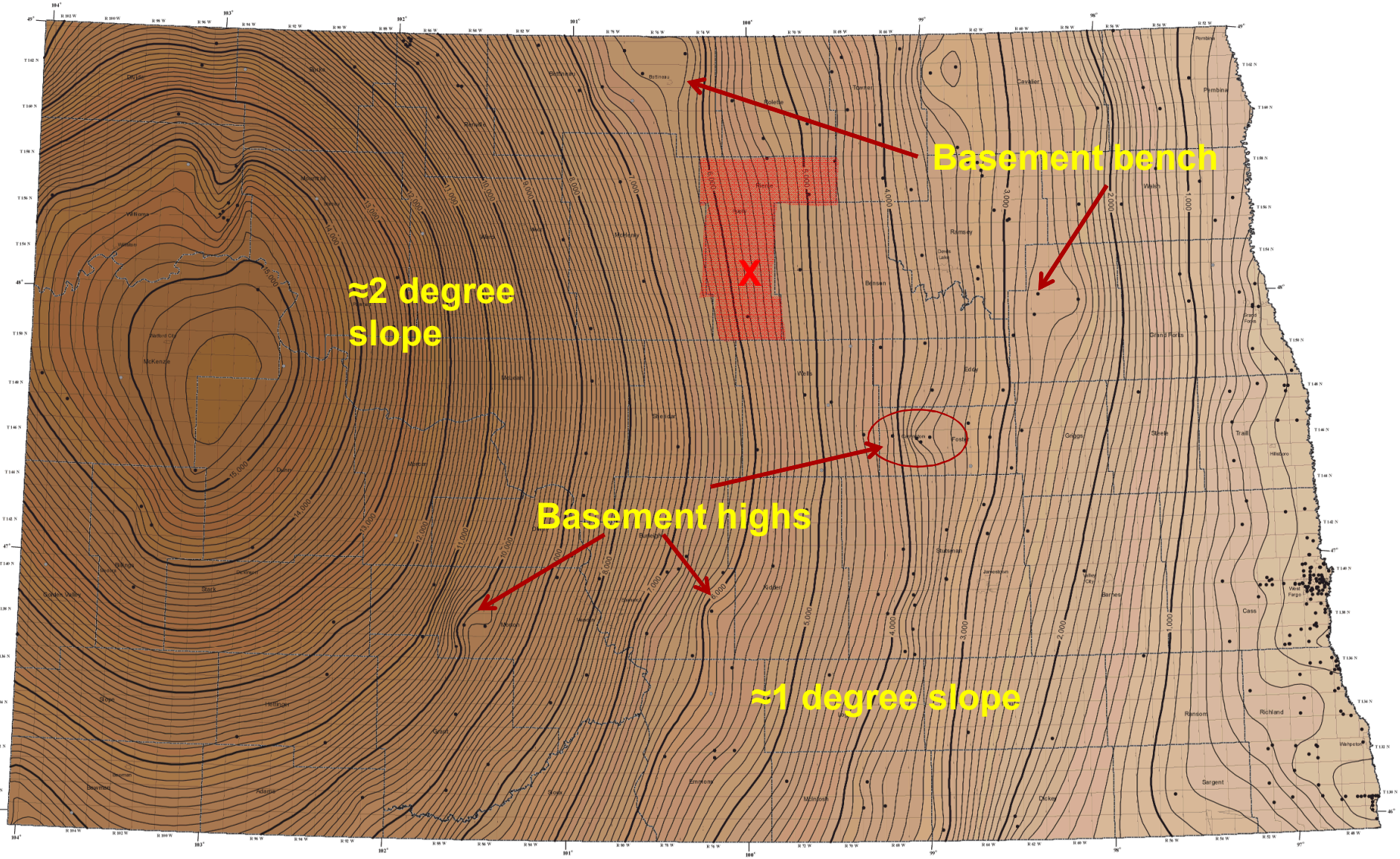

Interpreted Basement Surface (1988)

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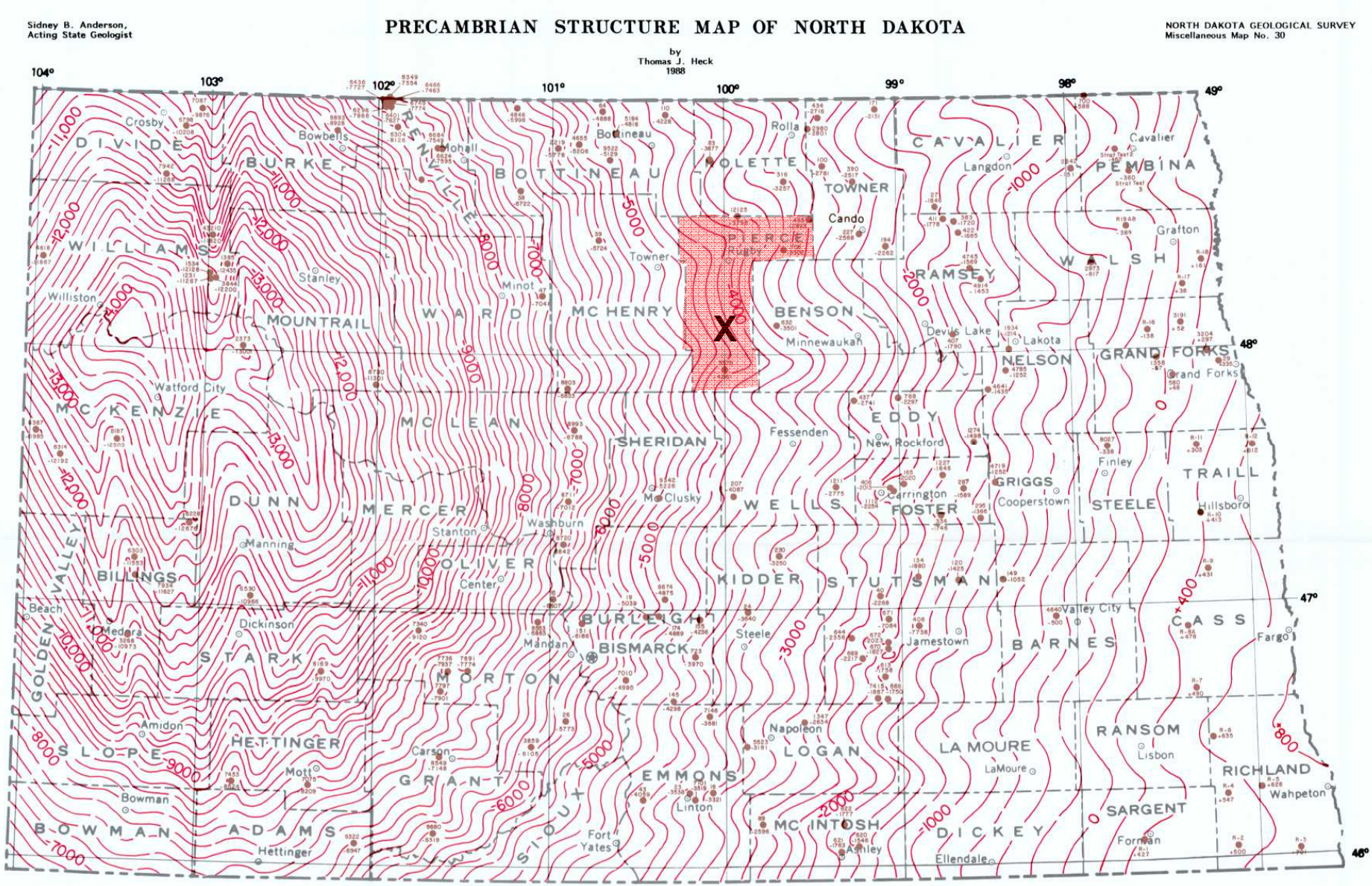
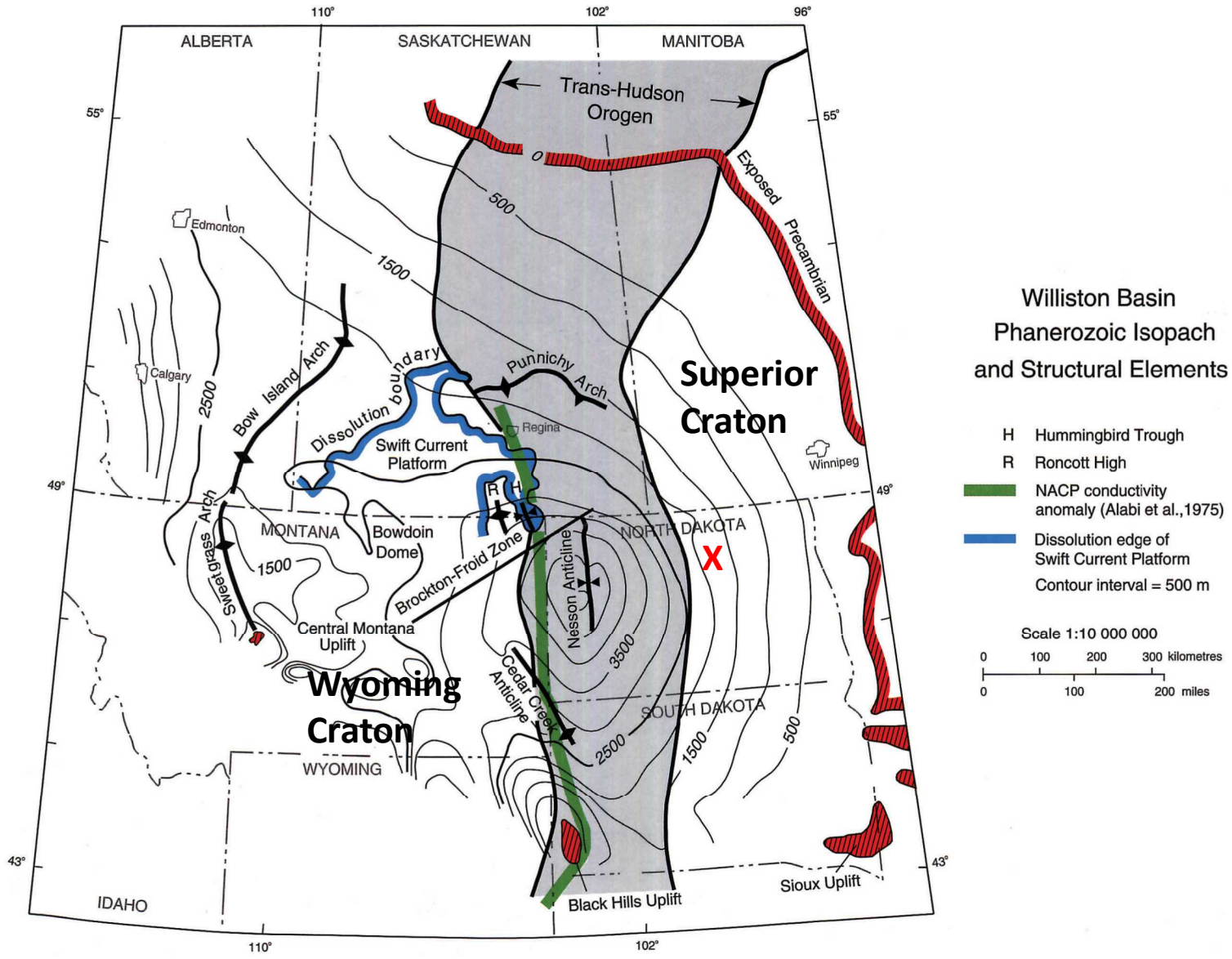


Basement Structure → Williston Basin



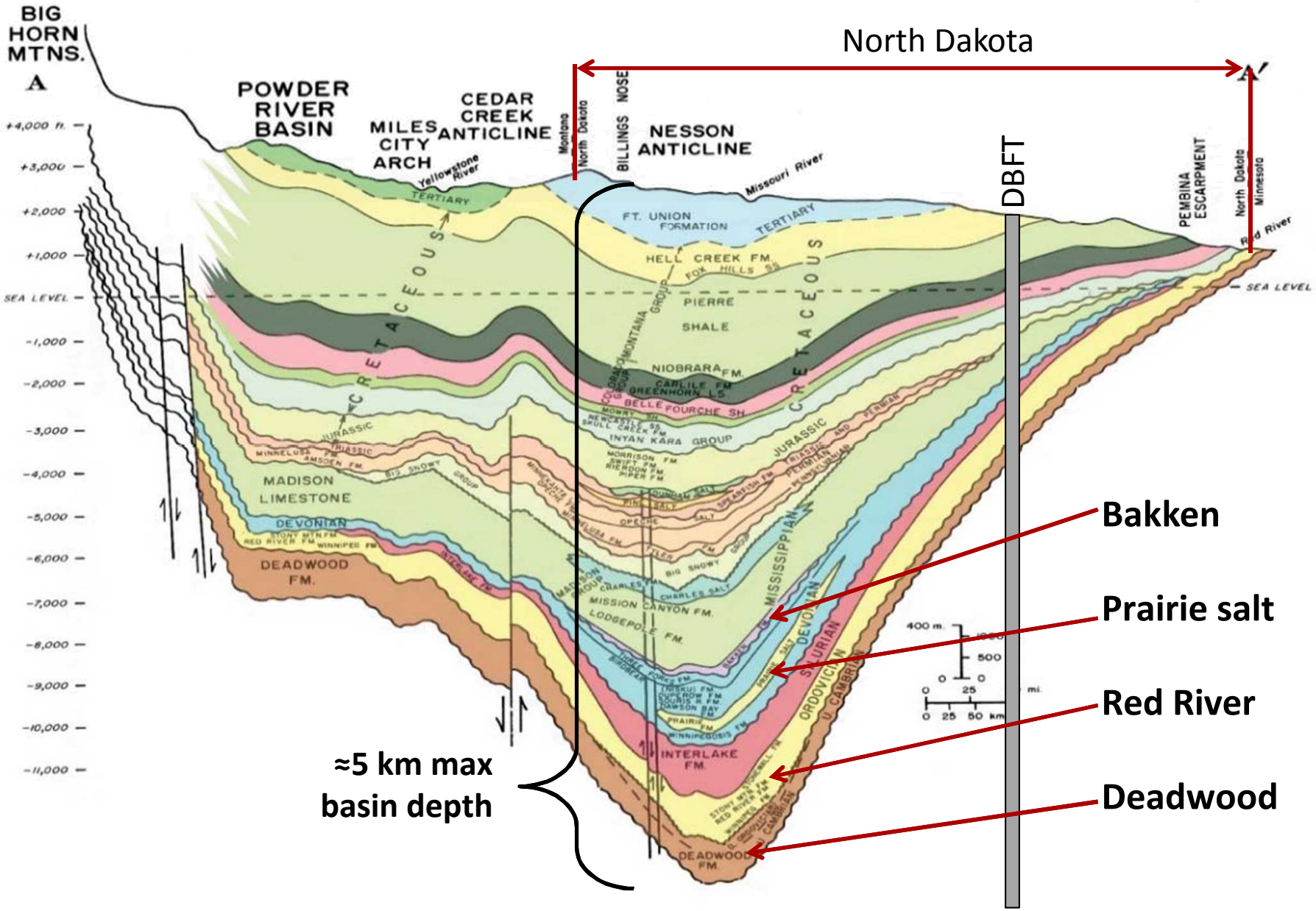
Williston Basin
Phanerozoic Isopach
and Structural Elements

H Hummingbird Trough
R Roncott High
NACP conductivity anomaly (Alabi et al.,1975)
Dissolution edge of Swift Current Platform
Contour interval = 500 m

Scale 1:10 000 000
0 100 200 300 kilometres
0 100 200 miles

Mossop & Shetsen (1994) [Eds], "Geological Atlas of the Western Canada Sedimentary Basin"

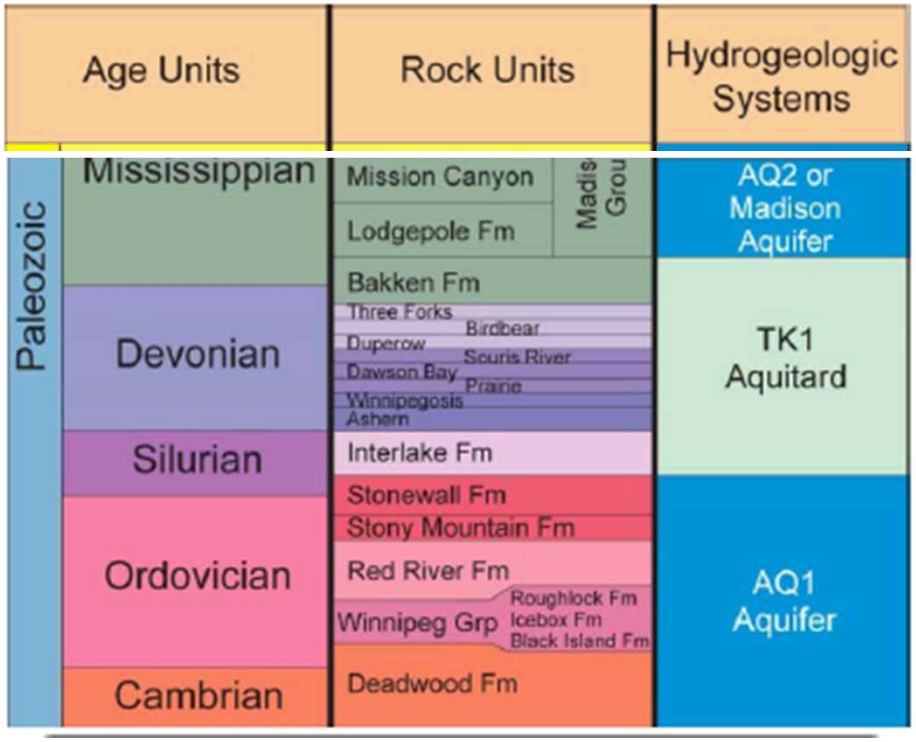
Williston Basin Cross-Section



Hydrogeologic system

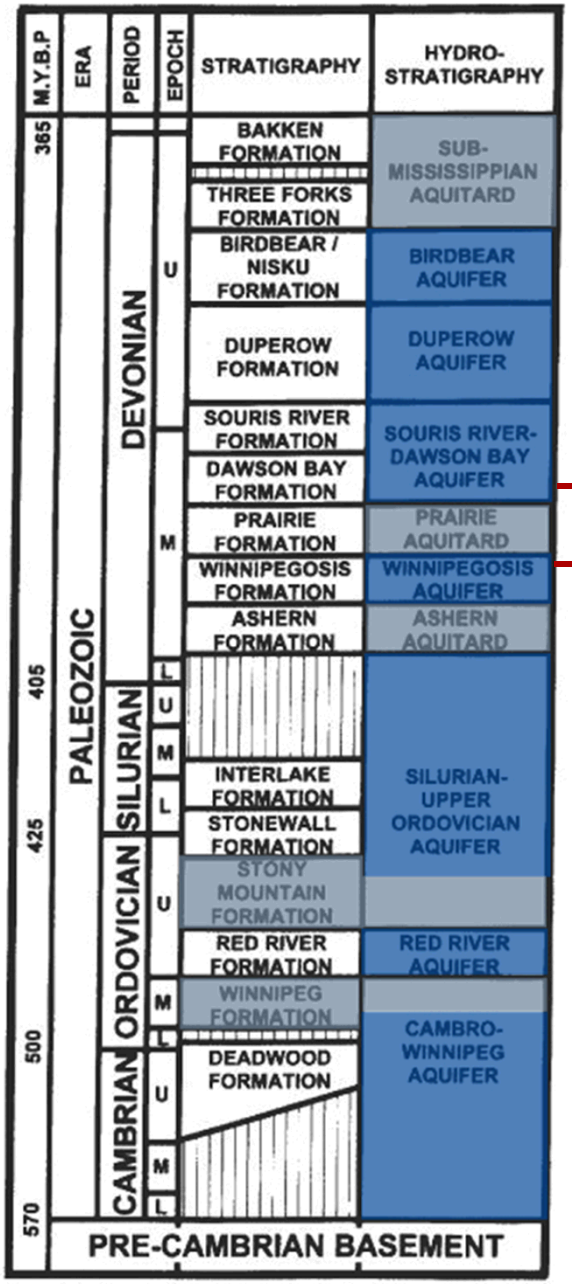
USGS in 1980s (Downey & Dinwiddie, 1988):

- Geology
- Hydraulic heads / numerical model



US-Canadian system of (Benn & Rostron, 1998)

- Geochemistry of produced waters
- Williston basin = 100 m isopach of Red River Fm



generally fresher

halite

generally briny

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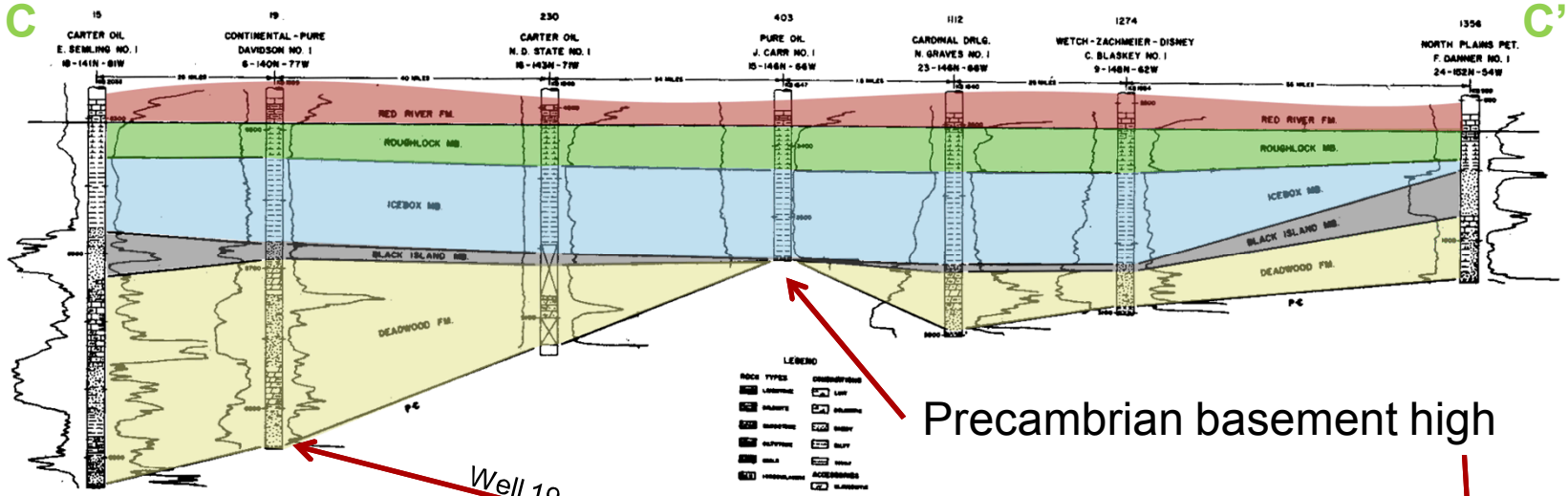

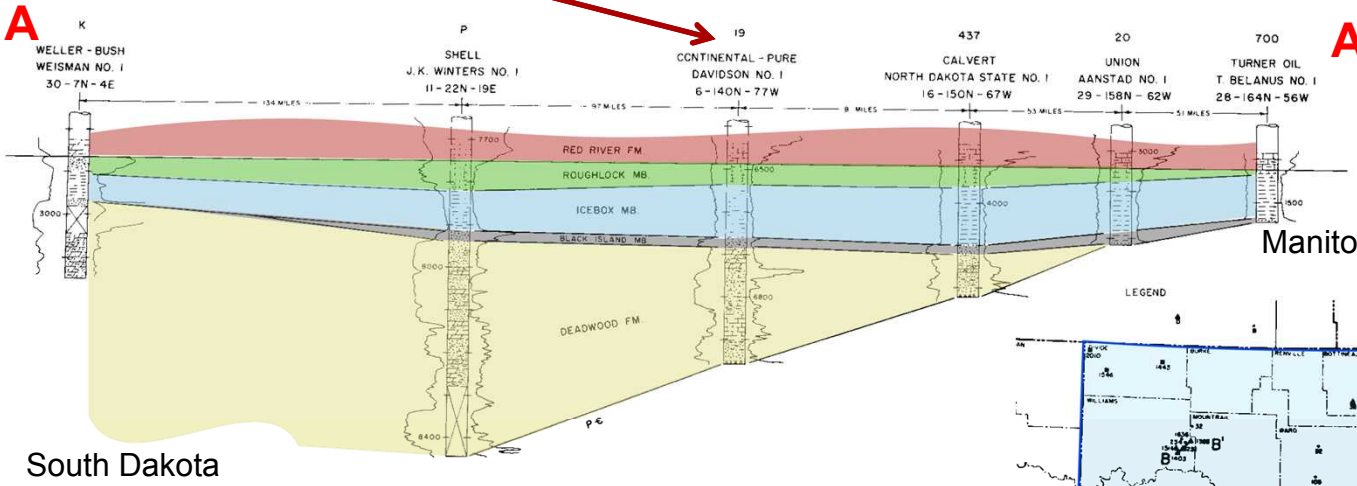

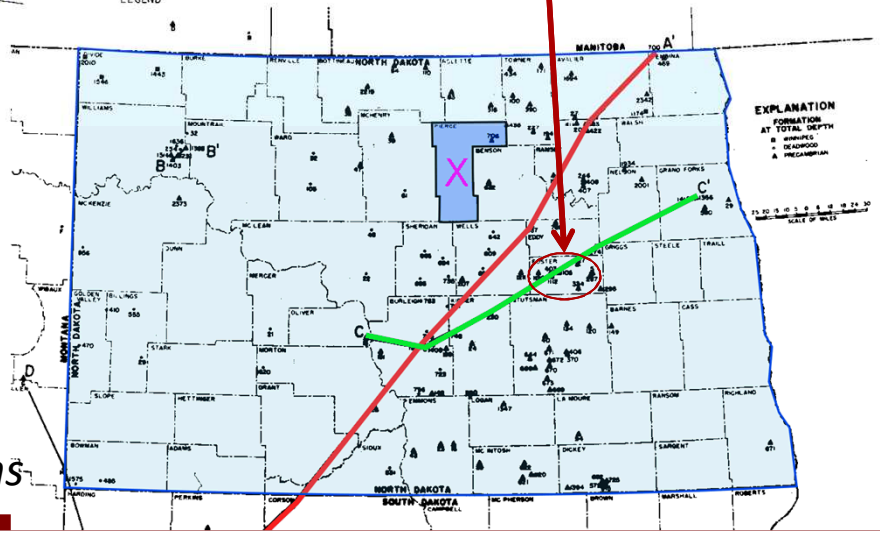

Deadwood Fm: clean quartzose sandstone with some carbonate + minor shale

Red River Fm: fossiliferous lime mudstone and wackestone (some dolomite)

In Canada sometimes: Yeoman + Herald Formations

NDGS Bulletin 35 (1960)

Williston Basin Flow

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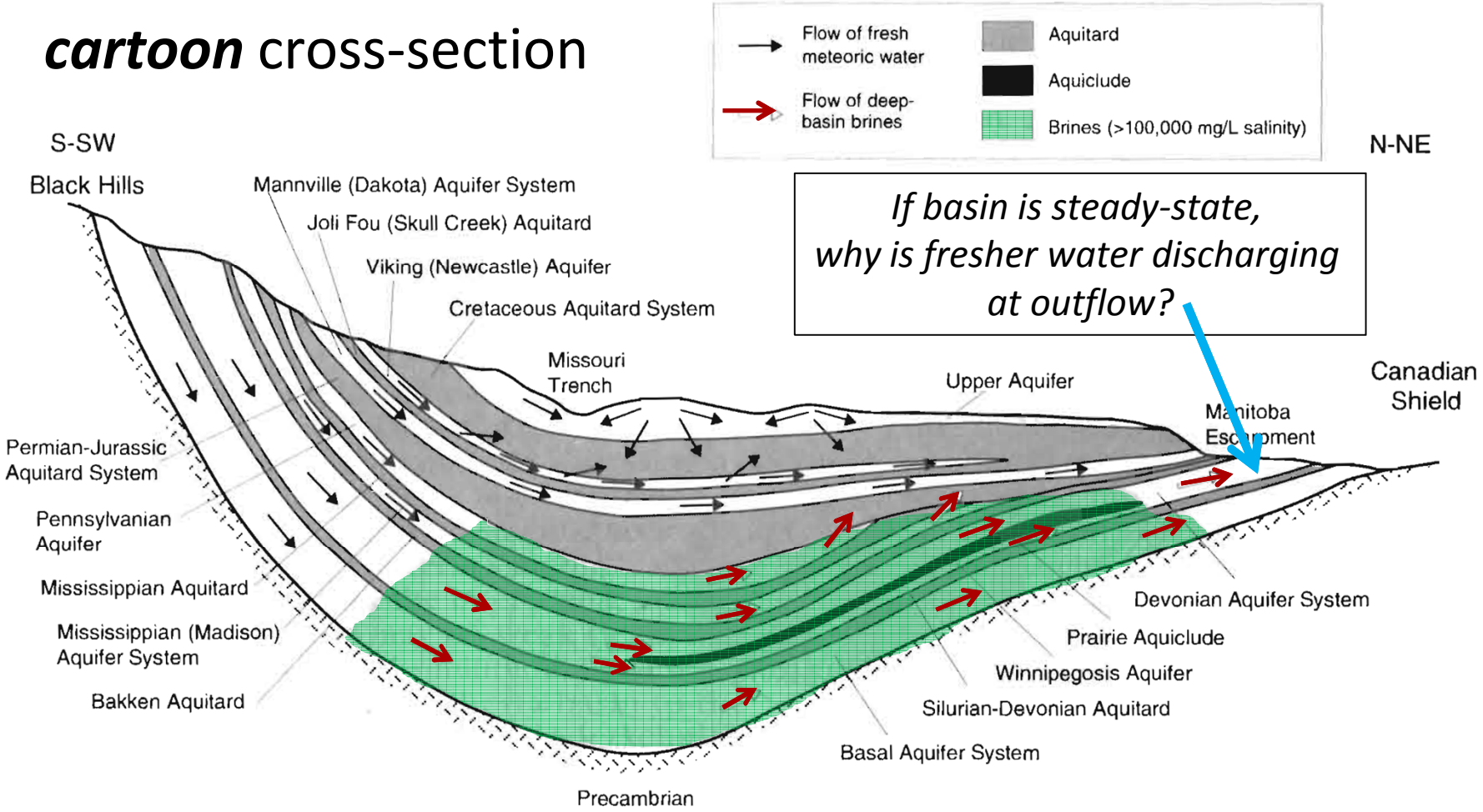
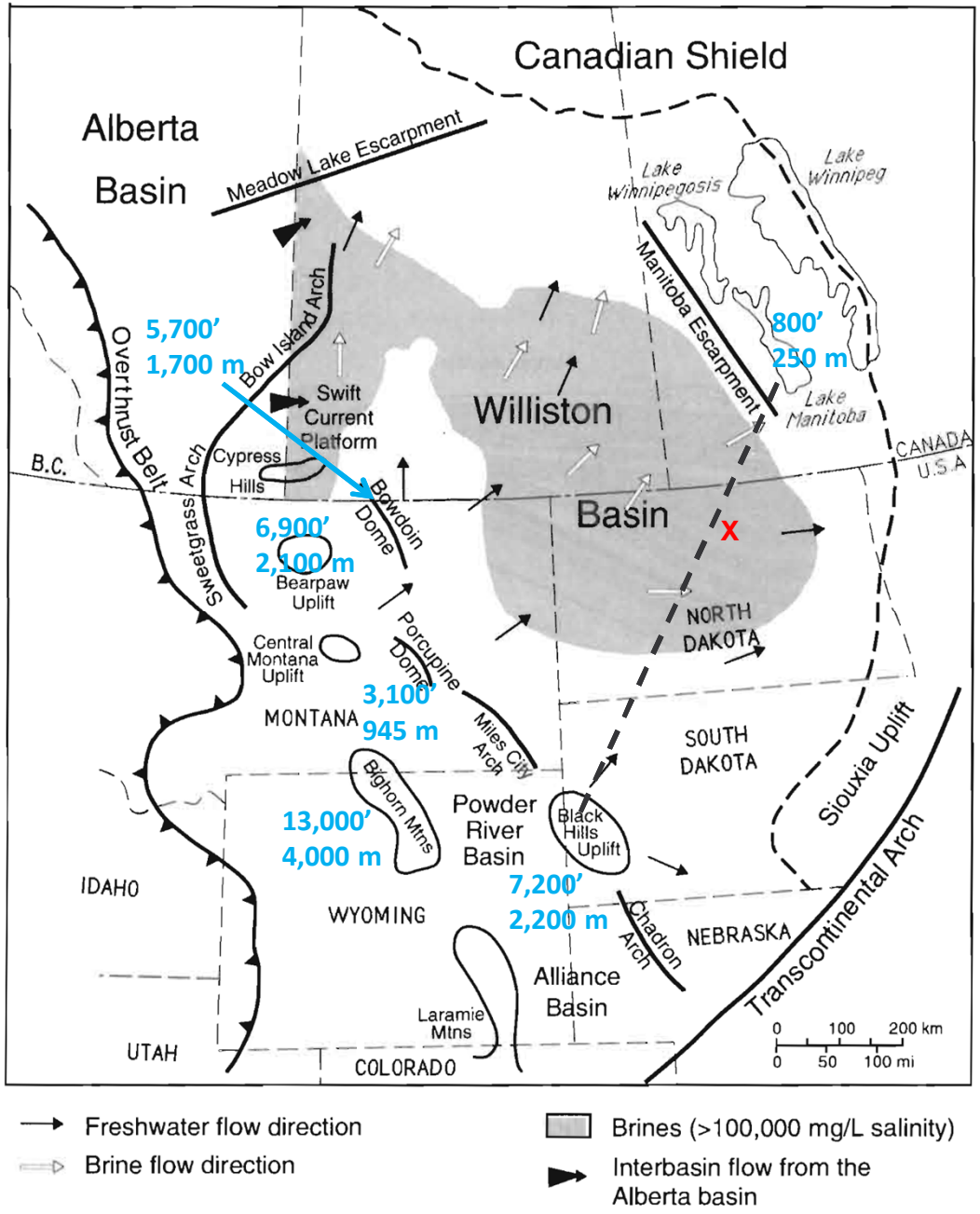
cartoon cross-section



Bachu & Hitchon (1996)



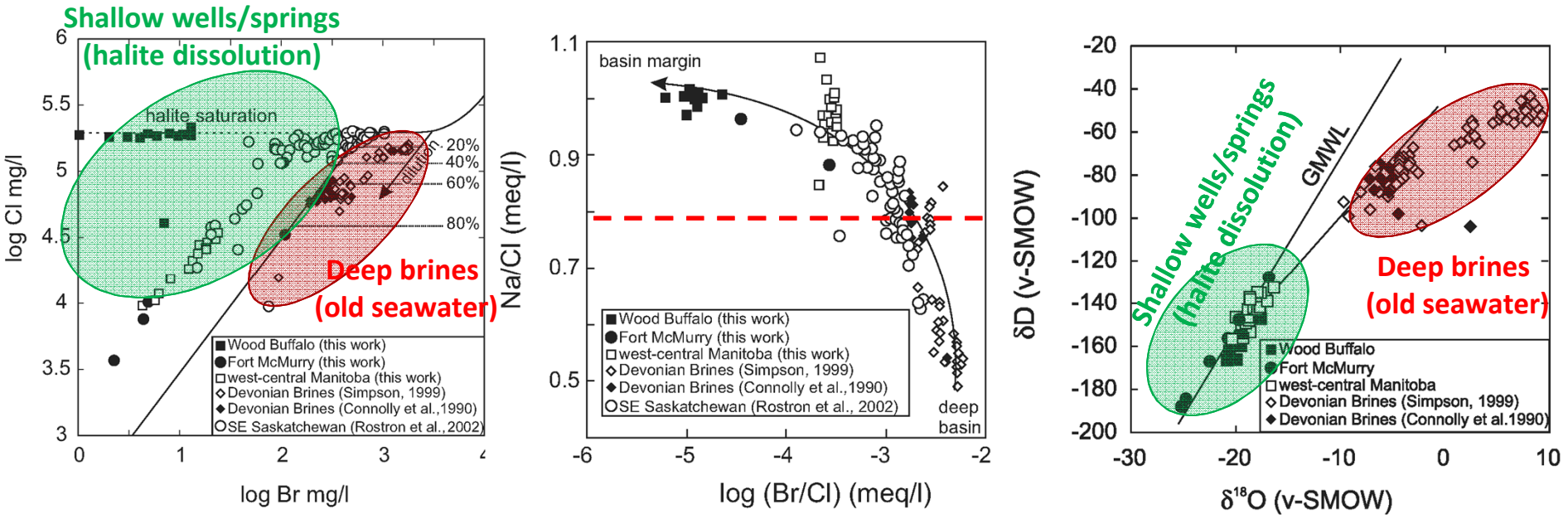
Williston basin

- Bowl-shaped
- Deepest part in western ND
- Connected to Alberta basin
- Lower part of basin filled with brine
- Recharge at high elevations in SW (MT + WY)
- Discharge at Red River + Lake Manitoba/Winnipegosis in Canada

Cambrian/Ordovician subcrops at both recharge and discharge points

Bachu & Hitchon (1996)

Nature of Deep Brines

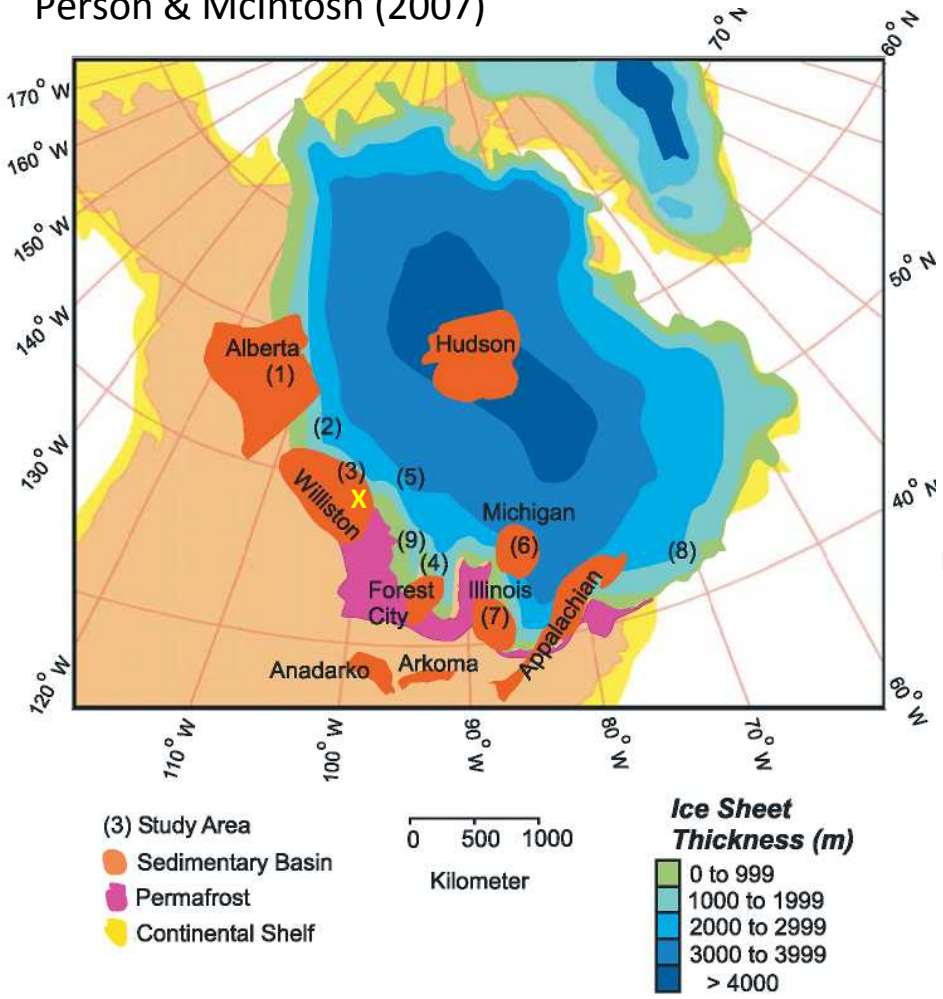


- **Br typically exluded from evaporite minerals**
  - **Lower Br/Cl ratio in halite vs. seawater**
  - **Na/Cl ratio <0.8 in deep brines (rock-water interactions buffering Na?)**
- **Deep brines have unique stable isotope signature**
- **Mixing between:**
  - **deep brine chemistry (old seawater) and**
  - **dissolved halite (glacial recharge near basin outflow)**

Grasby & Chen (2005)

Effects of Pleistocene Glaciation

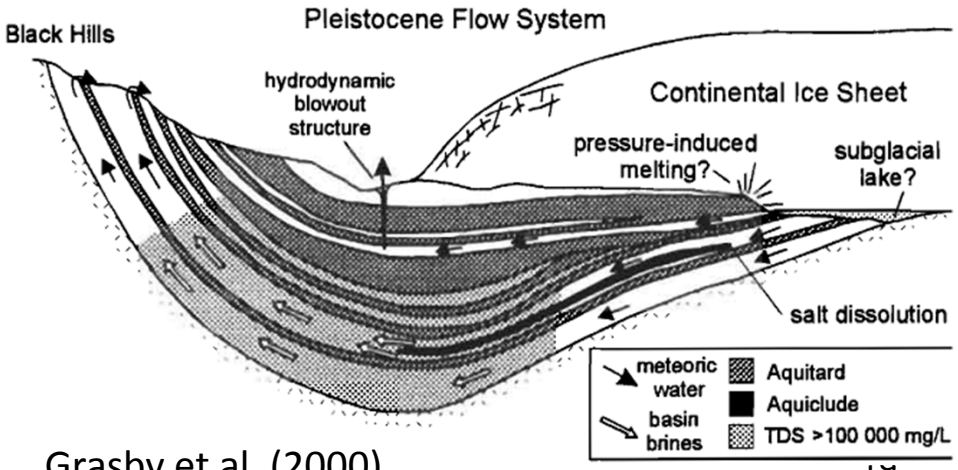
Person & McIntosh (2007)



<u>Last Glaciation (20k-14k years ago)</u>

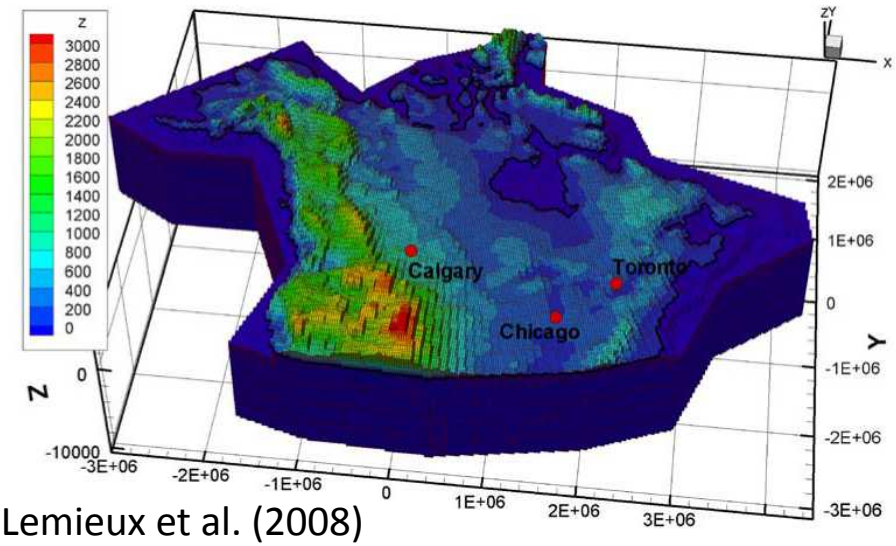
- 3+ km ice at basin outflow
- Flow direction reversed temporarily
- Geochemical evidence:
  - $\delta^{18}O$ near discharge
  - Aerobically degraded crude oils
  - Salt dissolution collapse features
- *<u>No evidence brines were displaced</u>*
- Glaciation also at 60k and 120k ya

<u>"Plug" flow in 2D cross section?</u>

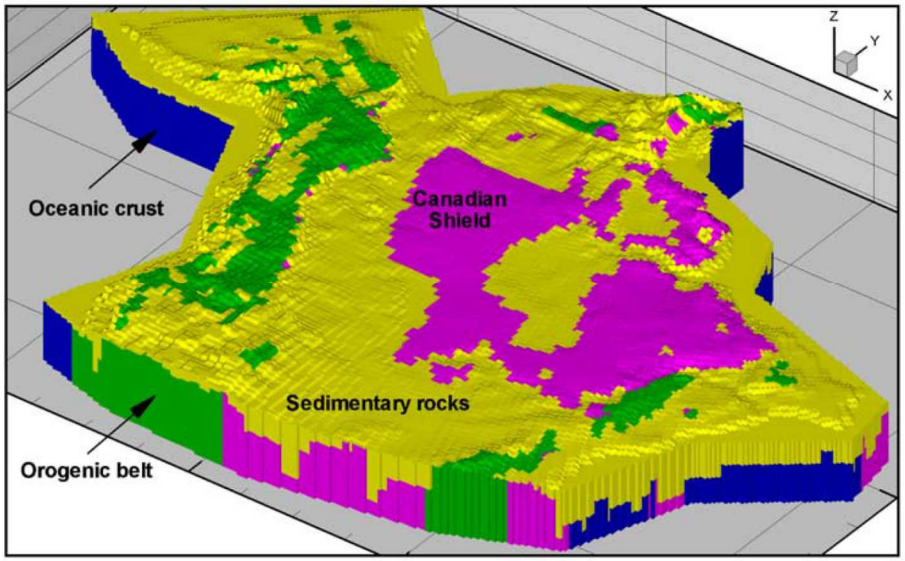


Grasby et al. (2000)

Continent-Scale GW Modeling



Lemieux et al. (2008)



HydroGeoSphere (Sudicky @ Waterloo)

- *Model grid*
  - *North America to 35° latitude*
  - *Elements 25 km areally*
  - *10 layers vertically*
  - *-10 km elevation to land surface*
  - *405,000 elements*
- *Groundwater flow*
  - *Density dependent*
  - *Loading term due to weight of ice*
- *Simplified solute transport*
- *Fully-coupled surface water flow*
- *Ice sheet model as input to BC*
- *4 material types*
- *Permeability decreases as exp(-depth)*

Results show deep penetration of glacial waters, but how realistic under basins?

Observations

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Basin Hydrogeologic Model

- 1980s USGS :: aquitards are “very leaky”
  - observe similar heads in aquifers across aquitards
- 1990-2000s GSC :: aquitards are “less leaky”
  - different water chemistry

Source of Brine

- 1980s USGS :: Prairie halite dissolution
- 1990-2000s GSC:: both evaporite dissolution (due to recharging glacial meltwater) and old seawater

Impacts of Glaciation

- GSC in early 2000s first pointed to significant changes 10k-14k years ago due to glaciation
- Modeling, but little definitive data outside Manitoba

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